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EXPERIMENTAL STUDY OF COLLINEAR SLOT ANTENNA
(AN APPLICATION OF BABINET'S PRINCIPLE)

By

Thaddeus Kuliszewski

September 6, 1954

Technical Report No. 202

Cruft Laboratory
Harvard University
Cambridge, Massachusetts

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Abstract

The effect of a high impedance transmission-line coupling on the current and phase relationship on a three-element, center-driven, collinear slot array at 10 cm wavelength is studied. A brief summary of theoretical results is followed by a detailed description of apparatus and the measuring procedures. Use is made of Babinet's principle in carrying out the measurements in an attempt to assess the validity of complementary slot techniques.

Results thus obtained are compared with the theory and with alternative measurements made on a similar structure employed at much lower frequency.

I

Introduction

The requirements of high directivity of any radiating system usually impose a number of conditions on the current and its relative phase distribution along the radiating surfaces.

In the case of a collinear array this condition in its most severe form requires unidirectional currents on all of the radiating elements. It has been shown by King [1], that in the case of a center driven collinear array, with two closely coupled parasites, the currents on any of the two outer elements are approximately equal in magnitude and opposite in phase. Such a current distribution is characterized by a field pattern having significant lobes in the phase of symmetry of the antenna as well as along symmetrical cones in the two hemispheres. Although such a field pattern may be desired for some applications, its directivity is obviously much lower and in order to improve it some methods of reversing the phase must be employed.

A rather obvious method would be of course, to drive each element individually in phase a situation which is far from being ideal since the presence of transmission-line feeders in a non-neutral plane complicates the field pattern. An alternative, and far more convenient method was analyzed by King [1]. The principal advantage of this method lies in its simplicity. A three element array, consisting of a center-driven and two collinear elements coupled to the central unit by high-impedance transmission lines displays the desirable properties of unidirectional currents. The high-impedance transmission line consists, for structural reasons of a quarter-wavelength short-circuited stub, and acts as a phase-reversing network.

It is the subject of this experimental study to confirm and check the semi-quantitative analysis of such a structure. This is in a sense a complementary study as an identical structure was investigated recently by Tang [2], the difference being in method and the medium of measurements. Tang has carried out his investigation for a resonant array at 50 cm wavelength, using the image-plane techniques. The present study is concerned with measurements at 10 cm wavelength and employs the complementary slot techniques. Thus, besides being a check on the analytical results it is also a study in the application of Babinet's principle.

A brief exposition of this principle seems to be in order at this point, although there are several excellent papers available on this subject [3,4,5] and related applications. In effect, Babinet's principle as applied to the problem of complementary slots holds that any plane system of current-carrying conductors can be represented by an equivalent arrangement of slots cut in an infinite, perfectly conducting and infinitely thin screen. The slots have to be driven in such a way as to establish the required correspondence between the magnitic field of the wire system and the electric field of the slots [4]. Specifically, then, the electric field distribution across the slot system is said to be a measure of the magnetic field or current distribution on the wire structure. This correspondence has been confirmed experimentally in several studies [5], and although it is subject to limitations, due to the imposed physically unrealizable conditions, it does constitute a realizable basis for an alternative, or, as in the case of unsymmetrical structures, for the only available experimental technique. The symmetrical structures employed at very short wavelength can, of course, be studied using an image plane and the similitude principle.

The results of this study, reinforce the validity of Babinet's Principle though none of the severe conditions, mentioned above was fully satisfied. The description of the experimental procedures, used in connection with the study of field or current and phase distribution on a complementary collinear slot array is given elsewhere in this report. A brief summary of pertinent theoretical results, is given in the following section.

II

Summary of Theoretical Considerations

The antenna investigated here is essentially a two dimensional structure and as yet, has not been analyzed rigorously. However, a semi-quantitative analysis has been advanced by King [1] for the case of a quarter wavelength short transmission line coupling. King considers two parallel problems, one, symmetrical with all three units driven in phase and another, with the two outer units driven in phase opposition. The solution of the two problems, superimposed, yields the desired information about the original, center-driven array. For the in-phase or symmetrical problem, the effect of the quarter wavelength phase reversing stub on the antenna current distribution is insignificant as the impedance presented by the stub to equal and opposite currents is extremely high and the radiation from the line practically negligible. Under these conditions, the symmetrical problem reduces to one analyzed very extensively, namely to collinear array with each element driven individually, and in phase. The current for such a problem is known to be nearly sinusoidal except for slight assemetry on outer units equal in magnitude and in phase on all elements. The antisymmetrical problem presents a little more complicated picture. King resolves in into a roughly equivalent collinear array with the center element of electrical half-length $\beta_o h = \pi$ and the outer units asymmetrically driven. The currents on such an array are approximately those of a dipole of this same length and are much smaller than an antenna for which $\beta_0 h = \pi/2$. It is then permissible to say that the superimposed solution of the two problems is approximately equal to that of a symmetrical case with currents effectively reversed in phase. Obviously, additional currents are maintained on the antenna and the coupling line, and as was estimated by Tang [2] their contributions to radiation fields is not necessarily negligible, although it is small as compared with the field produced by codirectional, symmetrical currents. Tang has also established that, in general the phase reversal may be expected to take place at the total length of the coupled unit and the line equal to an odd multiple of a quarter-wavelength. The length of the center element is, according to Tang, unimportant so far as the phase reversal is concerned. To summarize, then the theory predicts for a quarter-wavelength short-circuited transmission line coupling, a nearly sinusoidal, equal and codirectional currents on all elements. This information, in addition to the known current distribution for a center-driven array with two collinear parasites which it maybe repeated, is sinusoidal, equal in magnitude and opposite in phase constitutes a sufficient criterion, by which the results of this experimental study can be judged. A more detailed exposition of the underlying theory can of course be found in the quoted references.

III

Experimental Procedures

The objectives of this study and its intended method of execution require a relatively simple experimental set-up. Its construction was primarily determined by the condition implied in Babinet's principle and the simplicity called for by a limited time. The apparatus used in this study is shown in Fig. 1. It consists essentially of an aluminum ground screen [5] 4 feet by 6, elevated some 3 feet above the floor. In its center is a rectangular opening, 8 by 10.5 inches, in which a plate containing the desired slot configurations is placed. Shown in the picture is also the metallic supension bridge and a movable probe, having 2 degrees of freedom and some 30 cm range in the direction parallel to the slots.

The probe is of an electric type and is made of a 52 ohm coaxial cable, (.031 x .031 inches) with a protruding (.5 cm long) center conductor. The

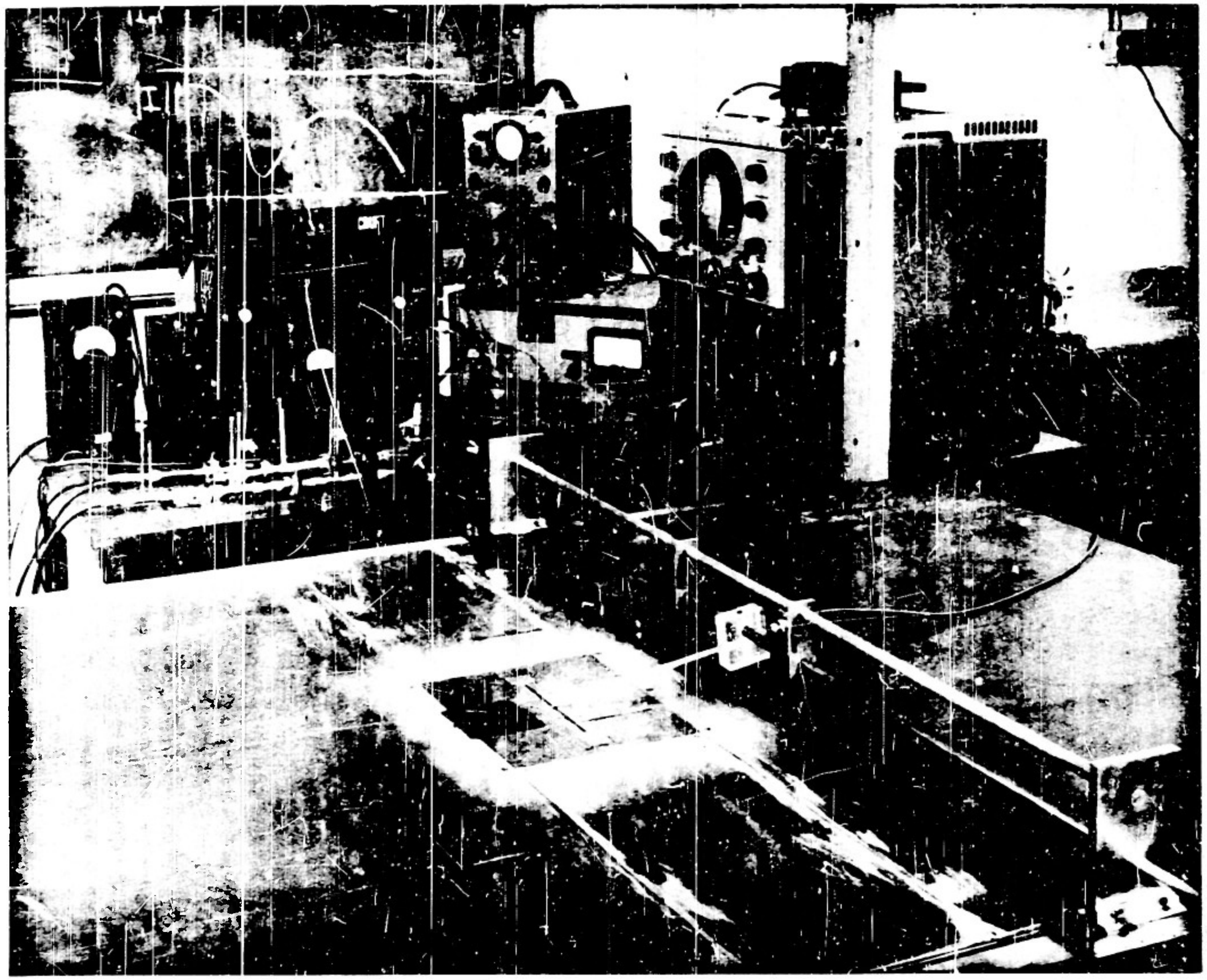


FIG. 1 GENERAL VIEW OF THE SCREEN, COLLINEAR SLOT ARRAY AND MEASURING EQUIPMENT

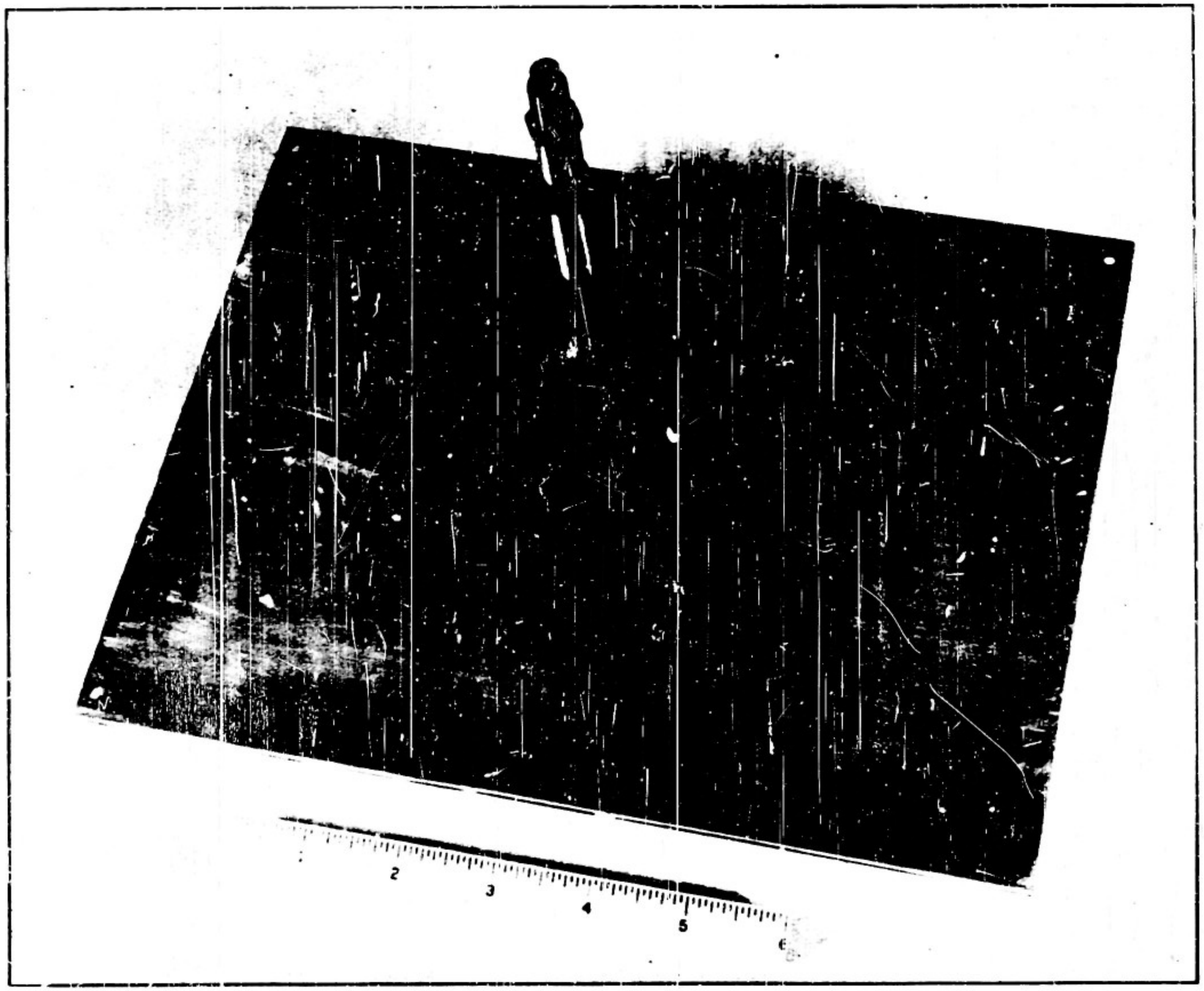
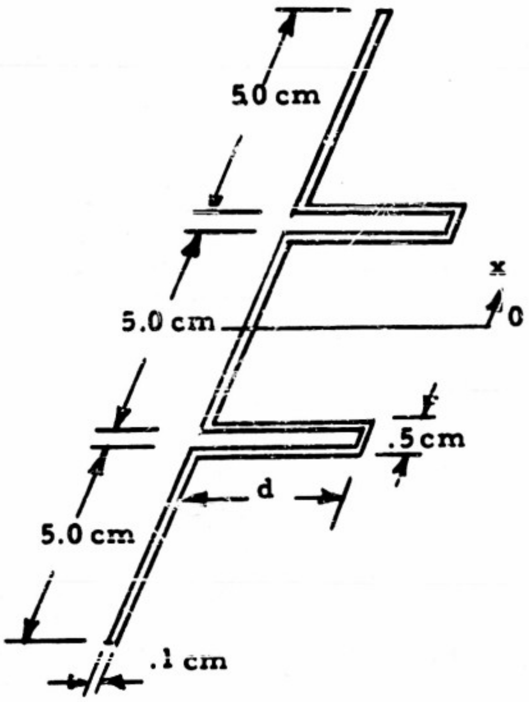


FIG. 2 VIEW OF THE ANTENNA PLATE WITH TWO-WIRE TRANSMISSION LINE FEEDER CONNECTED ACROSS THE SLOT

cable is supported by an 8 inch slotted polystyrene rod attached to a transition block, also made of polystyrene. For constructional reasons, the axis of a suspended probe forms a 10 degree angle with the screen, thus making it possible for the probe to sample the field at an elevation less than .1 cm from the plane containing the slots. The slot feeder, shown in Fig. 2, consists of a two-wire transmission line derived from a coaxial line and connected across the center slot in its plane of symmetry. The plate* containing the slots is made of brass and measures $10\frac{1}{2}$ x 8 x $\frac{1}{8}$ inches. In its center there are cut three collinear slots, coupled by a slot equivalent of the transmission line of adjustable length d. All pertinent dimensions are reproduced in the sketch of Fig. 3 and it is only necessary here to point out that they represent a



λ = 10.0 cm

$\Omega = 2 \ln \frac{2h}{a} = 10.6$

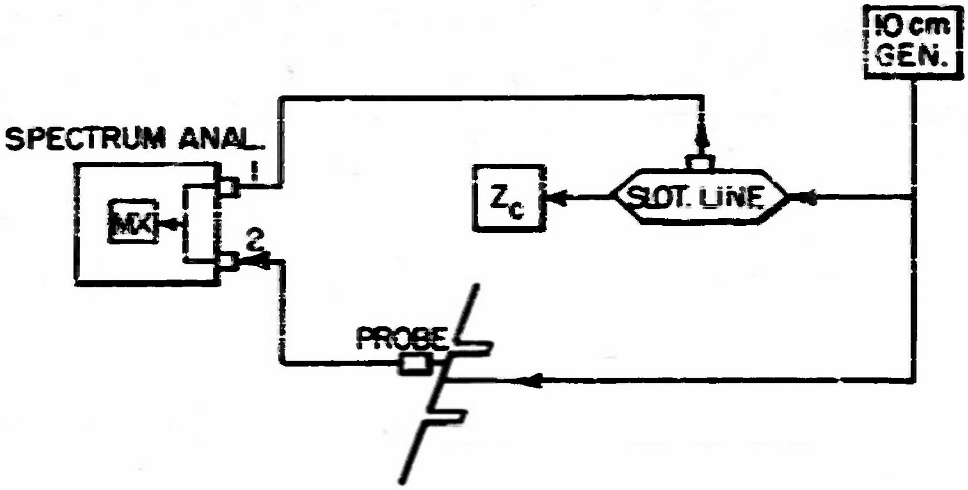
Fig. 3 Basic Dimensions and Notation

* Originally designed by T. K. Menon, of Cruft Laboratory

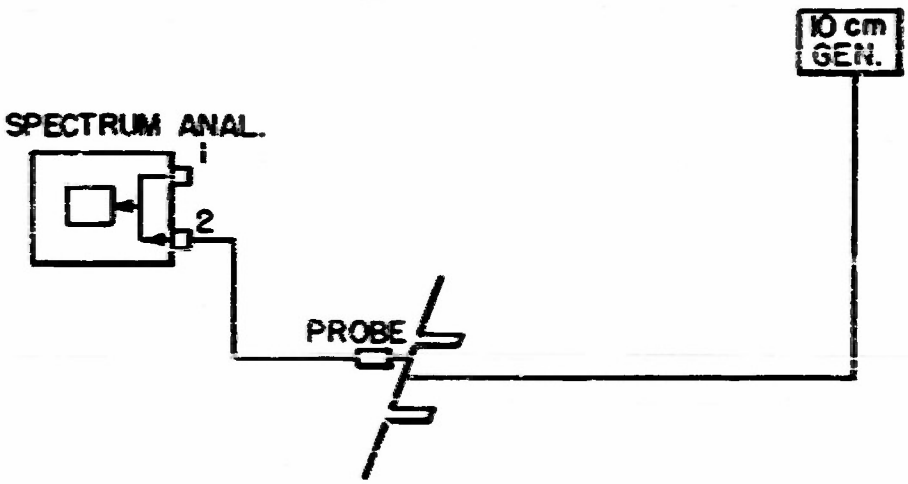
typical resonant structure of an equivalent expansion factor, defined for a wire structure as $\Omega = 2\ \ln\frac{2h}{a} = 10.6$ and with the usual conditions for a nonradiating transmission line well satisfied. The array is excited by an unmodulated signal derived from the 3000 mc transmitter using single klystron tube of the Sperry 410R type. Two alternative methods for phase and amplitude measurements were devised. Of these, only the one shown in Fig. 4 has proved to be useful for reasons of its greater sensitivity to the very weak signal sampled by the probe. In this method use is made of the Vectron Spectrum Analyzer Model SA10 for both phase and amplitude measurements. In the phase-measuring procedure two signals one derived from a flat coaxial slotted line and the other from the probe, are compared in the spectrum analyzer. This is made possible as the analyzer has two separate input terminals connected to a common mixer. The typical measurement of the relative phase of a signal sampled along the array relative in respect to the phase of a signal at the center of an array taken as 0° degrees consists then of minimizing the reading on the spectrum analyzer and noting the differences in wavelength traveled by a probe on the slotted line. The minima occur whenever the reference signals is 180 degrees out of phase with the signal under test. It may be added that for sharp minima both reference and sampled signals should have comparable magnitudes.

It is rather obvious that the apparatus described here is a source of a number of residual errors, although it is difficult to estimate their significance. First, the conditions of infinite conductivity, extent and thickness are not quite satisfied, particularly that of thickness. Second, the field sampled across the slot by the probe may include contributions from the transmission-line as well as from the surface of the screen, although it is believed that the contributions from slots predominate. Third, the inequality in the elevation of the plate may introduce considerable error in the amplitude measurements. The presence of a metallic bridge above the surface of the screen is not believed to be responsibe for any field distortion and if so, it is maintained consistently throughout the experiment. Among other possible sources of inaccuracies two more can be mentioned: the small phase shift resulting in the use of an attenuator in the phase measurements and possible mismatch of the reference line. As already remarked, it is difficult to estimate to what extent the enumerated errors affect the results. It is this author's belief, that the only reliable criterion to be used in this case is the consistency and reproducibility of the measured quantities and their plausibility from the point of view of theory and known alternative measurements.

It is, then, with this knowledge, that we can proceed next to the discussion



a) RELATIVE PHASE MEASUREMENT



b) AMPLITUDE MEASUREMENT

FIGURE 4

of the results and their evaluation.

IV

Results

The experimental results are contained in Fig. 5 to 14. They were recorded with the collinear array excited at 2.99 kmc and the VSWR of the slotted line less than 1.05. The presence of nonlinear elements (crystals) has made it necessary to calibrate the system and this information is presented in Figs. 13 and 14. Consequently, all remaining results are corrected according to this information. The relative magnitudes of the sampled electric field as a function of position along the array are shown in Figs. 5,7, and 9. These are the important cases of a resonant array coupled by a short-circuited transmission line of variable length d. Three curves, corresponding to d = 0, d = 2.5 cm and d = 5.0 cm are shown. Owing to the symmetry of the array only half of the distribution needs to be plotted. The results are in agreement with the theory, and are comparable to similar results obtained by Andrews [6] and Tang [2]. The curves follow sine function closely, thus justifying the common assumption of such an idealized distribution. The ratio of amplitudes is 1.0, 1.74 and 0.7 respectively. This is shown more explicitely in Fig. 11 where the ratio of magnitude of the field at center of a driven element to the magnitude of the field at a center of a coupled element is plotted as a function of variable length d. The curve oscillates irregularly about the average value 1.0. Plotted in the same figure is also the magnitude of the field at the center of the driven elements; it shows similar oscillations as the length of transmission-line coupling d is varied.

The results of the phase measurements are shown in Figs. 6, 8, 10 and 12. In Figs. 6, 8 and 10 the relative phase, referred to the center of the array as a function of position, is shown for three values of d. Except for regions of discontinuity, the results are in excellent agreement with the theory. They show clearly the effect of coupling and the expected reversal of phase for $d = \frac{\lambda}{4}$.

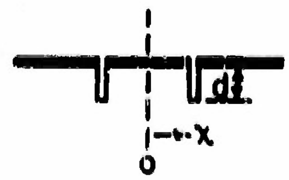
A curve of a relative phase at the center of a coupled element as a function of d is shown in Fig. 12. This curve, in addition to being a confirmation for critical values of d, shows the continuity with which the process of the phase reversal takes place. As before, the results compare excellently with similar results obtained by Andrews [7], Tang [2] and Hatch [8]. There exists some ambiguity as to the sign of the measured phase but this information is of no particular interest as it is the relative phase difference that is included in the computation of field pattern. For this reason, no attempt is made to assign any particular direction to the plotted curves, convenience in representation being the only criterion used.

There is no doubt about the consistency and plausibility of the results. A few words, however need to be said about their reproducibility. The curves shown here are plotted from the best set of data of which five were taken for each quantity of interest. The deviation in individual sets were of an order of not more than 5 per cent with a number of almost identical readings. It is, therefore absolutely certain that the general tendencies of these measurements can be reproduced with sufficient dependability although in view of the medium in which they are performed, some discrepancies within the indicated limit can be expected.

V

Conclusion

The results as presented in the preceding section permit the author to restate a few basic conclusions concerning their agreement with theory and the validity of experimental approach. The results of King's analysis [1], summarized in Section 2 of this report seem to be fully confirmed by the present measurements. Specifically, the current distribution along the collinear array has been shown to be nearly sinusoidal for the three important cases of transmission-line coupling of length $d = 0$, $d = \frac{\lambda}{4}$ and $d = \frac{\lambda}{2}$. The slight asymmetry anticipated in the distribution of current on the coupled element is not evident from the results, but it should be emphasized that such an asymmetry was arrived at for an idealized case of three individual in-phase driven elements and does represent only the significant radiating component of current. The ratio of the amplitudes of currents of the driven and parasitic element is nearly 1.0, although this value is most true for $d = 0$. There is excellent agreement in so far as the phase measurements are concerned. The current on the parasite is nearly 180° degrees out of phase with the current on the driven element for $d = 0$ and $d = \frac{\lambda}{2}$. For $d = \frac{\lambda}{4}$ both currents are in phase. For each value of <u>d</u>, the phase is found to be nearly constant along the respective elements. Such behavior was also predicted by the theory.



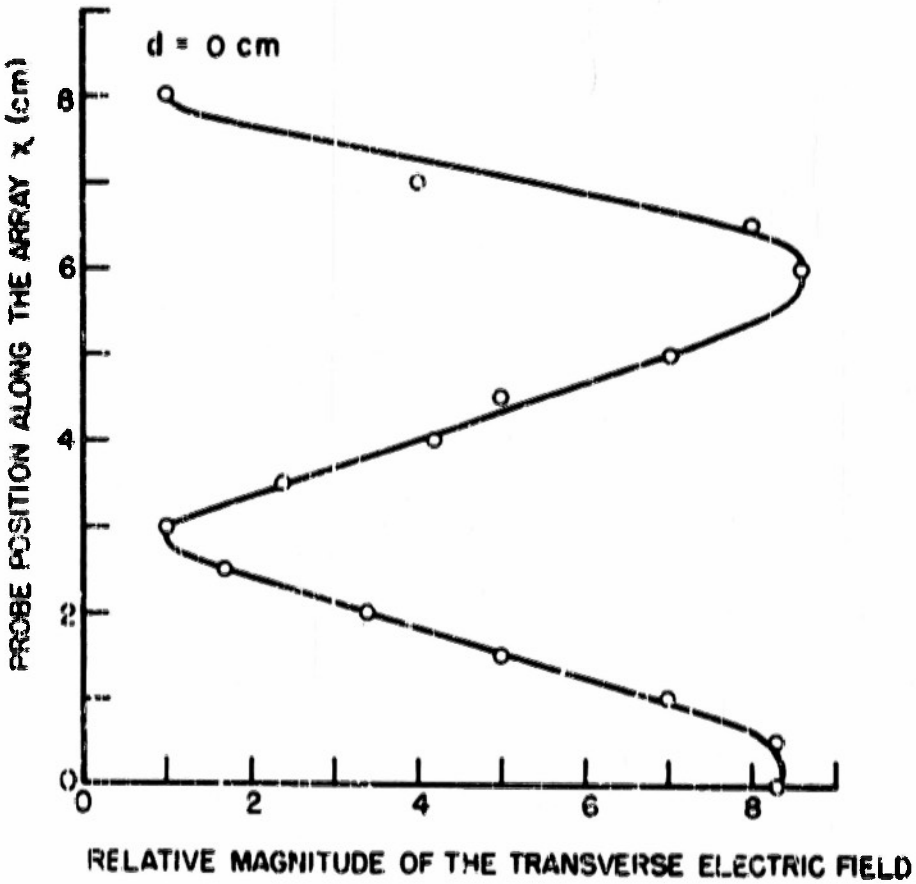


FIGURE 5

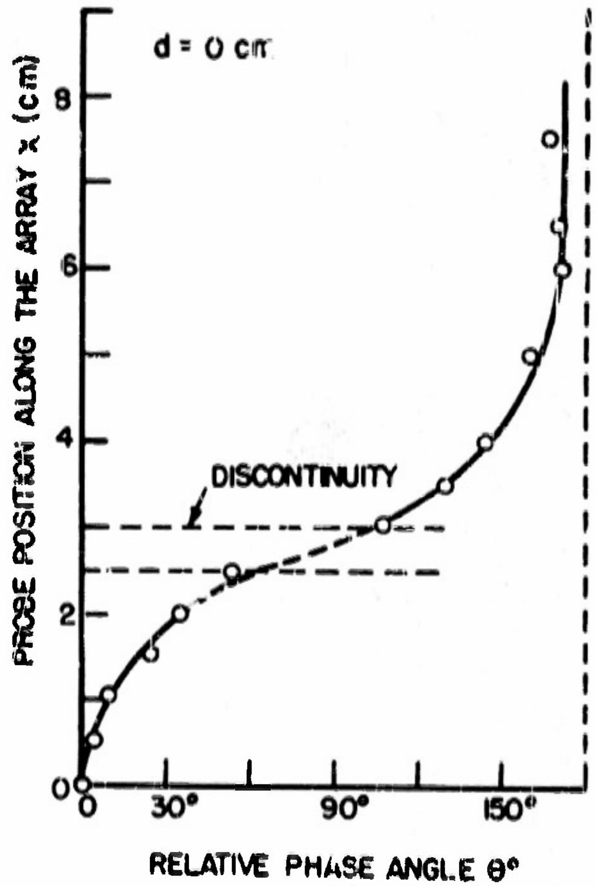
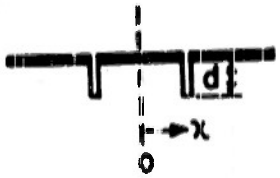


FIGURE 6



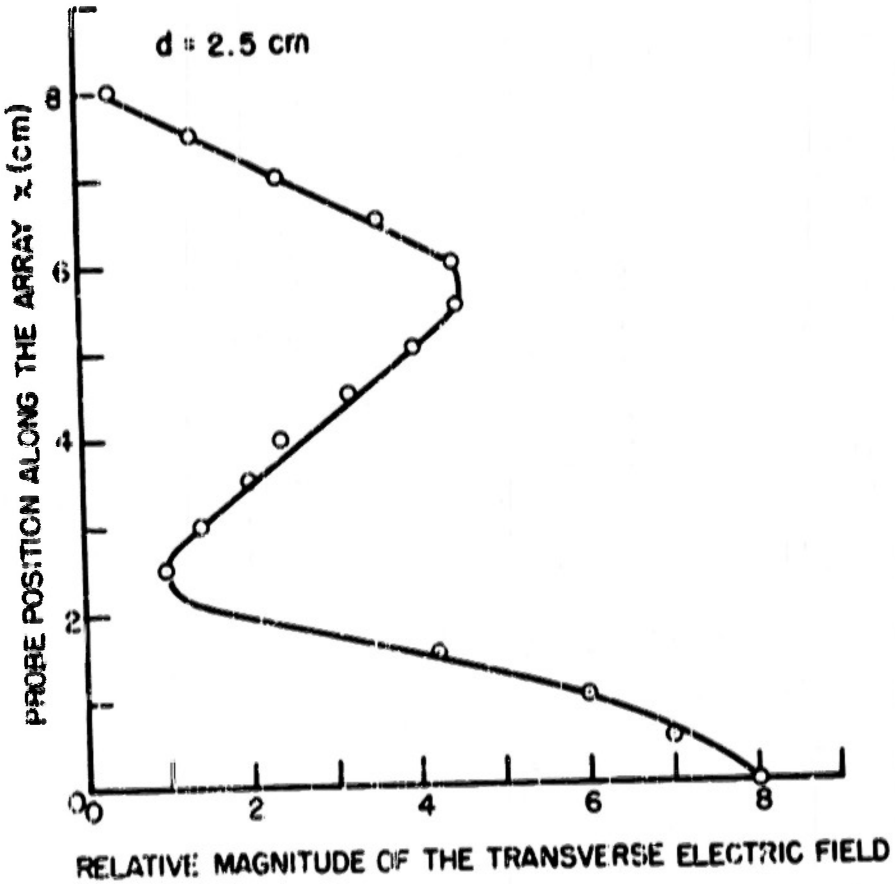


FIGURE 7

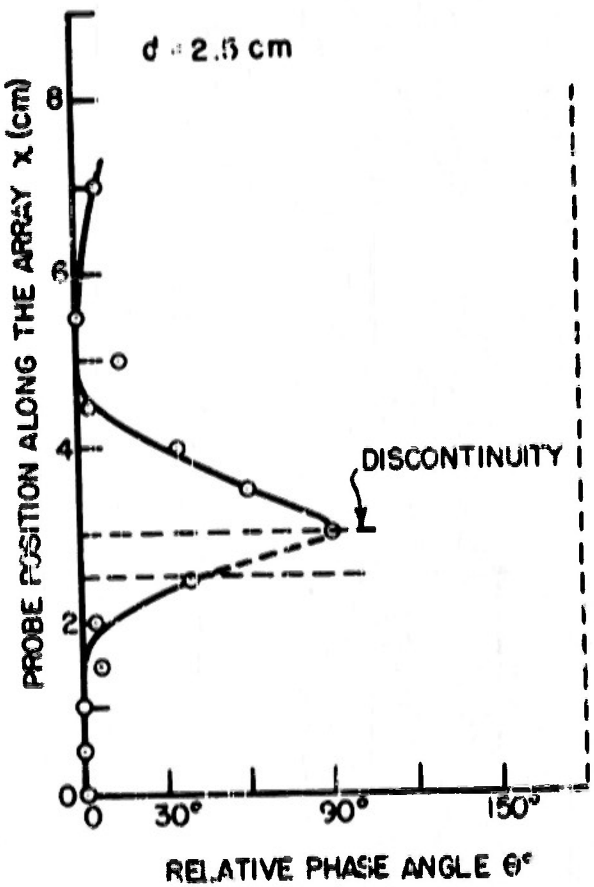
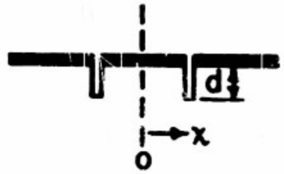


FIGURE 8



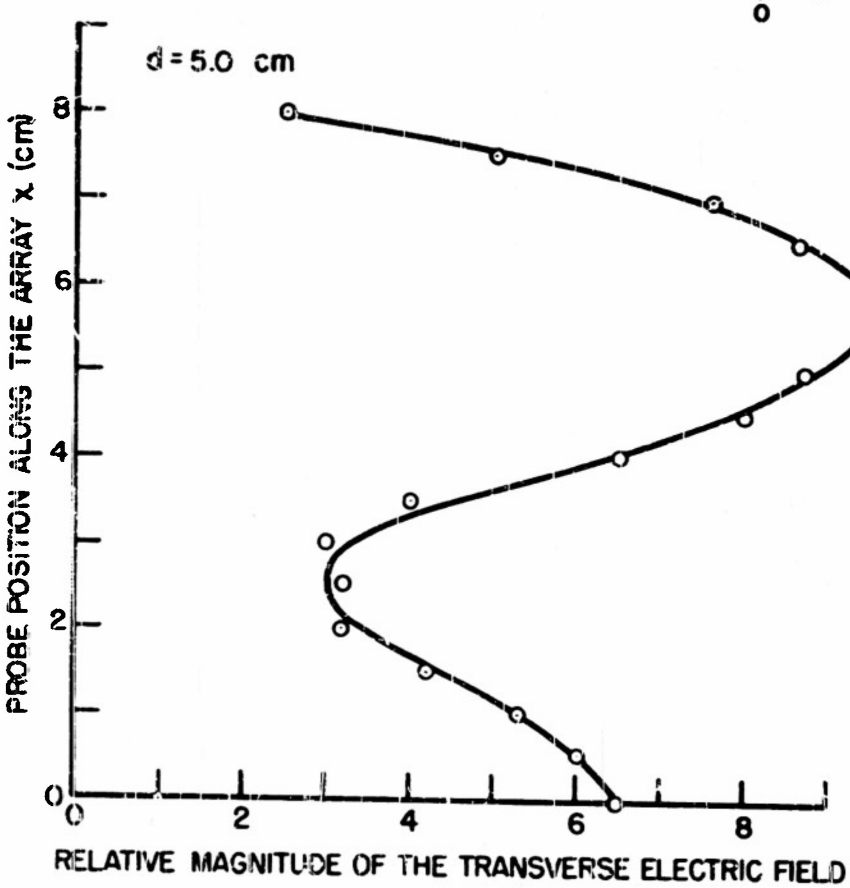


FIGURE 9

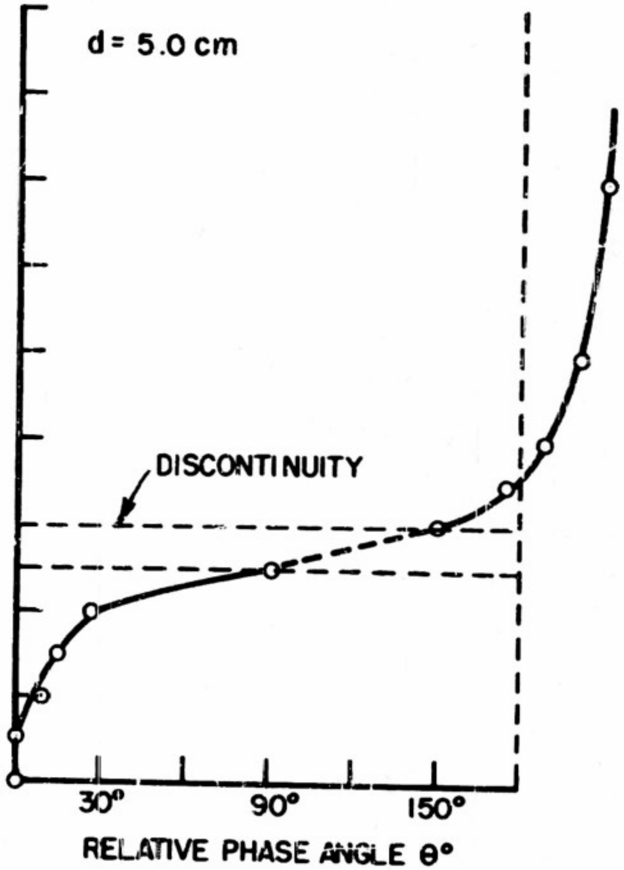
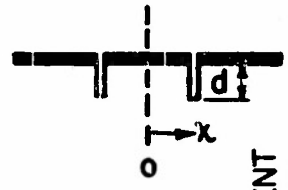


FIGURE 10



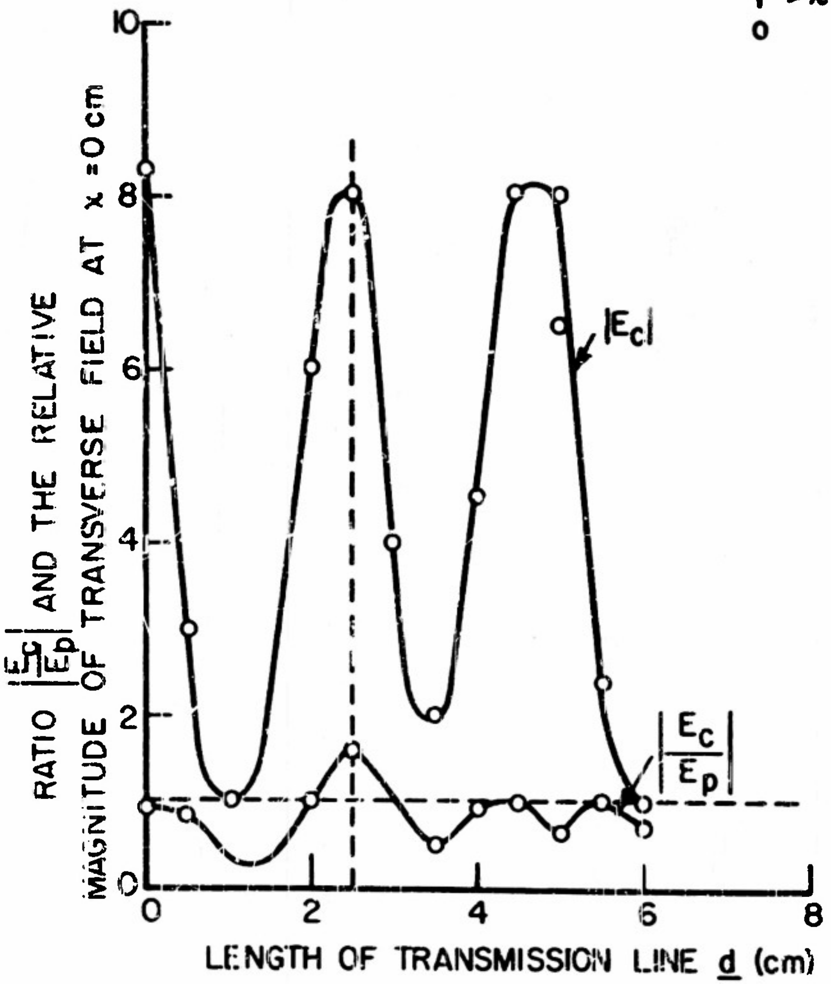


FIGURE 11

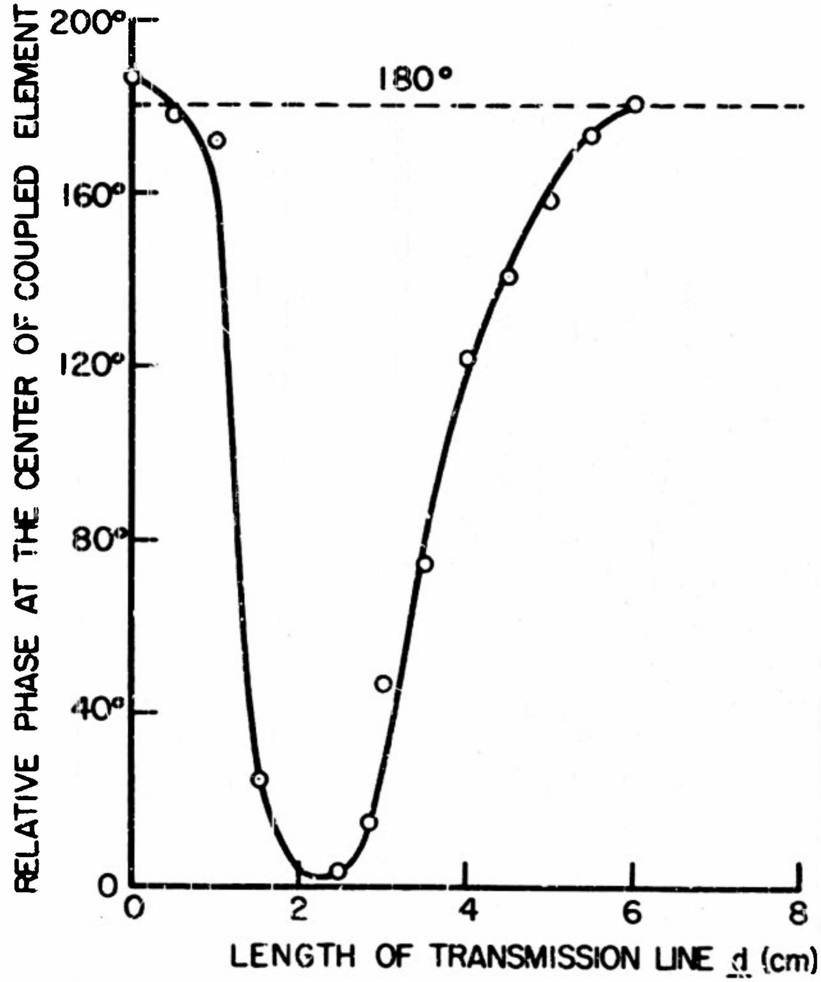


FIGURE 12

CALIBRATION CURVES

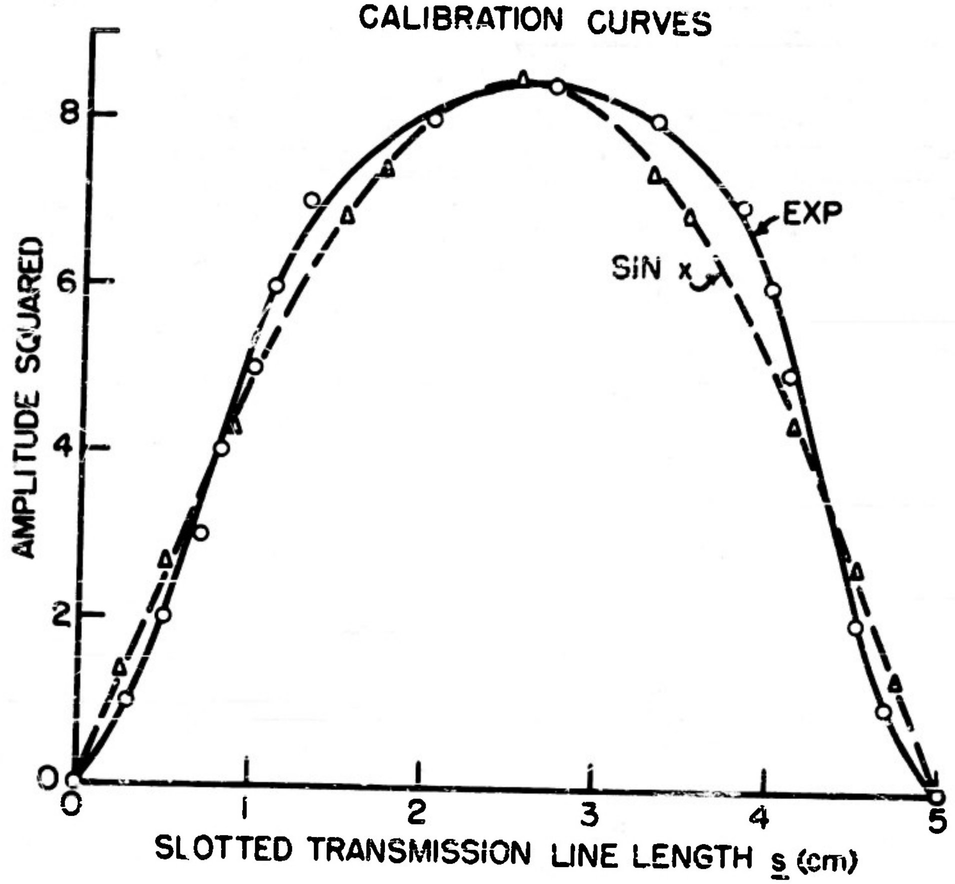


FIGURE 13

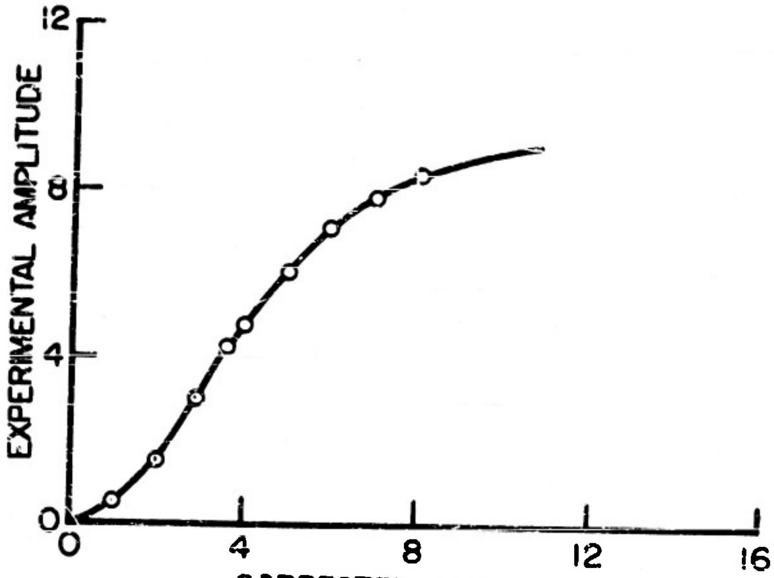


FIGURE 14

The phase reversal of current on the coupled elements, found to be true in this study, constitutes the greatest single confirmation of the theory and is especially valuable in assessing the validity of Babinet's principle and the experimental techniques employed. Further confirmation of this argument is evident from the comparison made with alternative procedures and results discussed previously.

It appears to this writer that the present study establishes another precedence in support of complementary system technique. The simplicity and relative accuracy with which the measurements can be performed renders it a valuable tool in investigating antenna structures not accessible to an alternative procedures. Obviously, caution must be exercised in its use as it is subject to conditions difficult to realize in practice. Further study on the limitation of this method and the significance of various errors would be a welcome undertaking.

Acknowledgment

The author wishes to express his thanks to Professor R. W. P. King for the opportunities provided to carry out this study. Thanks are also due to Dr. R. V. Row for his kind suggestions and final reading of the manuscript. Mr. J. Bates of the Machine Shop has assisted in the construction of the slot assembly and the suspension bridge.

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